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Discussion

Effective pulse compression in dispersion decreasing and nonlinearity increasing fibers

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ABSTRACT

We numerically demonstrate effective pulse compression in photonic crystal fibers with linearly decreasing dispersion and linearly increasing nonlinearity. The proposed fiber design can achieve nearly chirp-free and pedestal-free pulse compression and provides a feasible and a much simpler design in practice.

1. Introduction

Ultra-short pulses have attracted much interest recently because of its potential applications in high-capacity communications, optical metrology and biomedical optics [1–3]. Generally, ultra-short pulses can be generated from mode-locked lasers which are complex and costly. As an alternative, two widely used pulse compression techniques for achieving ultra-short pulses are the higher-order soliton pulse compression and adiabatic pulse compression [4]. The former one has a large compression factor within a short fiber length, but a high input power is needed and the compressed pulse suffers from significant pedestal generation. For compression factor of 60, up to 80% of the pulse energy is wasted in the pedestal [5]. In the adiabatic pulse compression, the compressed pulse maintains the transform-limited characteristics. But the adiabatic condition must be satisfied and the maximum compression factor is limited to about 20 [6]. For pulses broader than 5 ps, the fiber length required tends to be excessively long [6–8]. Recently, a technique known as self-similar analysis [9,10] has attracted much attention and has been used to study linearly chirped pulses in optical fibers and fiber amplifiers [11]. One of the advantages of this technique is the linear chirp facilitates efficient pulse compression and nearly chirp-free and pedestal-free pulse compression can be realized.

Recently, nearly chirp-free and pedestal-free self-similar pulse compression was demonstrated theoretically where the second-order dispersion decreases exponentially and the nonlinear coefficient keeps as a constant along fiber length [12], or dispersion as well as nonlinear coefficient varies exponentially [13]. Recent work [14] studies the optimal values of holey fiber parameters for both adiabatic and non-adiabatic soliton compression at 1550 nm where simultaneously decreasing dispersion and effective mode area are considered. Very recently, self-similar pulse compression at a near visible wavelength 850 nm was numerically demonstrated in a photonic crystal fiber (PCF) with the exponentially decreasing dispersion and exponentially increasing nonlinearity [15]. Pulse compression (1.64–0.357 ps) at 1554 nm was demonstrated both numerically and experimentally in a highly anomalous dispersive PCF with a dispersion value of 600 ps/nm/km [16]. In the context of the adiabatic pulse compression, the effect of different dispersion profiles is widely studied. In particular, [8] studies the effect of four different dispersion profiles (linear, hyperbolic, exponential and gaussian profile) on the performance of adiabatic pulse compression and concludes that the linear and gaussian dispersion profiles are nearly optimum in terms of the compressed pulse quality. However, no detailed study of different dispersion profiles for the self-similar pulse compression is provided. Considering the difficulties of fabricating a fiber with the exponentially varying dispersion and nonlinearity, in this paper, we present a detailed study of different linear profiles for the approximation of the exponential profile as required in the self-similar pulse compression. In the linear approximation, the compression factor keeps high, the pedestal remains small, and the time-bandwidth product is very close to the value of the transform limited hyperbolic secant pulse (0.315). Thanks to the high design flexibility of PCF and state of the art fiber fabrication techniques, we can engineer the required

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dispersion and nonlinearity profiles by changing PCF parameters such as pitch Λ and the air-hole diameter d [17–20]. Nearly adiabatic compression of 130 fs to 60 fs has been experimentally demonstrated in a dispersion decreasing holey fiber [21]. Over 15 times compression of pulses from 830 fs to 55 fs has been realized experimentally in 50 m long tapered PCFs with loss as low as 30 dB/km [22]. The paper is structured as follows. Section 2 describes the theoretical model. Section 3 makes a comparison of different linear profiles for the approximation of the exponential profile. Section 4 illustrates the importance of initial pulse chirp. Section 5 makes a comprehensive study of pulse compression by varying fiber length, initial dispersion and initial pulse width. Section 6 further considers the effect of third order dispersion effect. Finally, we propose the PCF design with the linearly varying dispersion and nonlinearity and conclude the paper.

2. Theoretical model

For ultra-short optical pulses (< 1 ps), it is necessary to include the higher-order dispersion and nonlinear effects (such as self-steepening and intrapulse Raman scattering), and the generalized nonlinear schrödinger equation (GNLSE) can be written as [3],

$$\frac{\partial E}{\partial z} + i\frac{\beta_2(z)}{2}\frac{\partial^2 E}{\partial t^2} + \frac{\alpha}{2}E = i\gamma(z)\left(1 + i\tau_{shock}\frac{\partial}{\partial t}\right) \times \left(E(z,t)\int_{-\infty}^{\infty} R(t') |E(z,t-t')|^2 dt'\right), \qquad (1)$$

where $E(z, t)$ is the slowly varying amplitude of the pulse envelope, z is the distance variable, t is the time variable, and α is the fiber loss. The dispersion and nonlinearity vary exponentially as $\beta_2(z) = \beta_{20}\exp(-\sigma z)$, $\gamma(z) = \gamma_0\exp(\eta z)$, where β_{20}, γ_0 and ς_{20} are the initial dispersion, nonlinearity and chirp coefficients. $\sigma = \varsigma_{20}\beta_{20}$ and η represent the decay rate of dispersion, and growth rate of nonlinearity, respectively. $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$ is the Raman response function where $f_R = 0.18$ and h_R is determined from the experimental fused silica Raman cross-section. $\tau_{shock} = 1/\omega_0$ and ω_0 is the center frequency. The loss coefficient (α) is a constant and equals to the nonlinearity growth rate (η), i.e., $\alpha = \eta$. The analytic solution of the chirped bright solitary wave for the exponentially decreasing dispersion and exponentially increasing nonlinearity is given in [13],

$$E(z,t) = \sqrt{\frac{|\beta_2(z)|}{\gamma(z)}}\frac{1}{T_0\exp(-\sigma z)} \times \operatorname{sech}\left(\frac{t - T_c}{T_0\exp(-\sigma z)}\right) \times \exp\left[i\varsigma_{10} + \frac{i\beta_{20}}{2\sigma T_0^2}\left[1 - \exp(\sigma z)\right] + \frac{i\sigma\exp(\sigma z)}{2\beta_{20}}(t - T_c)^2\right], \qquad (2)$$

for the typical nonlinear schrödinger equation (NLSE)

$$i\frac{\partial E}{\partial z} - \frac{\beta_2(z)}{2}\frac{\partial^2 E}{\partial t^2} + \gamma(z)|E|^2 E = 0. \qquad (3)$$

and T_c represents the center of the pulse and T_0 is the initial pulse width parameter. The corresponding compression factor for solution (Eq. (2)) is $\exp(\sigma L)$, where L is the fiber length.

3. Pulse compression in linear profile

In practice, manufacturing a fiber with exponentially varying dispersion and nonlinearity is still difficult. Here, we consider the use of a fiber with the linearly varying dispersion and nonlinearity. The initial pulse can be represented as $\sqrt{P_0}\operatorname{sech}(t/T_0)\exp(i\zeta_{20}t^2/2)$,

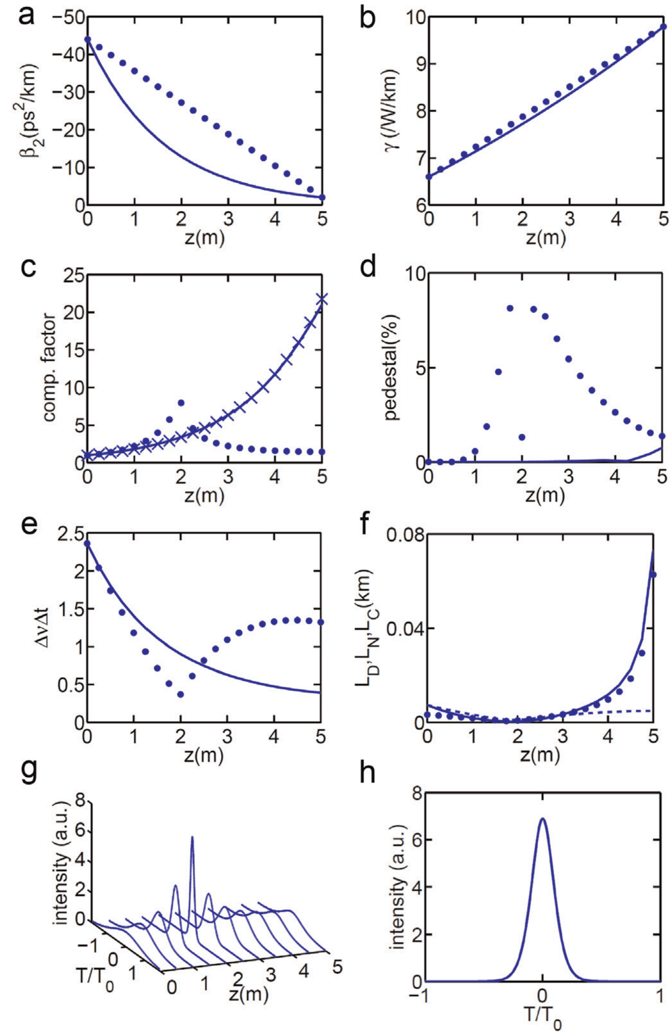

Fig. 1. Profile A: (a) dispersion and (b) nonlinearity in both exponential (solid line) and linear (dots) profiles; (c) compression factor in the ideal case (crosses), exponential profile (solid line) and linear approximation (dots); (d) pedestal (%) and (e) time-bandwidth product versus propagation length in the exponential profile (solid line) and linear approximation (dots); (f) L_D (solid line), L_N (dashed-line) and L_C (dots) versus propagation length in the linear approximation; (g) temporal evolution in the linear approximation; and (h) pulse shape at 2 m.

where $P_0 = |\beta_{20}|/\gamma_0/T_0^2$. For the exponentially varying dispersion and nonlinearity, we chose the parameters ($\beta_{20} = -44$ ps^2/km, $T_0 = 0.567$ ps, $\varsigma_{20} = -14$ THz^2, $\gamma_0 = 6.6$ W^{-1} km^{-1}, fiber length $L = 5$ m, $\sigma = 616$/km, and $\alpha = \eta = 78.8$/km, $\lambda_c = 1550$ nm) where the full width at half maximum (FWHM) of the initial pulse and compressed pulse are 1 ps and 45 fs, respectively. The dispersion and nonlinear coefficients in the linear approximation can be represented as $\beta_{2,L}(z) = k_{1,L}z + b_{1,L}$ and $\gamma_L(z) = k_{2,L}z + b_{2,L}$, where z, $\beta_{2,L}(z)$ and $\gamma_L(z)$ represent the fiber length, dispersion and nonlinear coefficient, respectively. For both exponential and linear profiles, the governing equation is Eq. (1).

3.1. Same initial and final dispersion/nonlinearity

For this linear profile, we assume linear and exponential profiles have same initial and final dispersion and nonlinearity. The corresponding linear approximation is $\beta_{2,L}(z) = 8395.56z - 44$ (ps^2/km) and $\gamma_L(z) = 637.4z + 6.6$ (W^{-1} km^{-1}). Fig. 1(a) and (b) plots dispersion and nonlinearity versus propagation length in the exponentially varying case (solid line) and its linear approximation